Internal Wave Energy Budget Studies in the South China Sea

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LONG-TERM GOALS

We are focused on understanding small-scale processes that influence the ocean's thermodynamic and dynamic properties on the sub-mesoscale (scales less than 10 km). This includes the role of turbulence in modifying the upper ocean temperature and density structure. In the South China Sea, large-amplitude, nonlinear waves force turbulence in the seasonally variable continental shelf region. New observational data is sought for use in characterizing turbulence phenomena, and for parameterizing processes in models.

OBJECTIVES

This program was focused on measuring the dissipation rate of mechanical energy on the shallow continental shelf and the Dongsha Plateau of the South China Sea. The measurements are being used to examine the energy dynamics of small-scale wave processes in relation to tidal forcing. The measurements are the first dissipation observations from a region where extreme-amplitude, nonlinear internal waves loose their energy in shallow water.

APPROACH

During the NLIWI program, we conducted two turbulence surveys in the South China Sea (Figure 1). Our work in the South China Sea began in 2005 during the pilot phase of the program, when we conducted a survey on the continental shelf using a shallow water turbulence system. This survey was conducted from the OR1 during the period April 11-20 with Joe Wang (NTU), Glen Gawarkiewicz (WHOI), and Ching-Sang Chiu (NPS). Our work in 2005 was also coordinated with the acoustics effort being conducted by OASIS from the OR3. During 2007, we returned to the SCS to measure turbulence levels on the Dongsha Plateau. This survey was done from the OR3 during the period April 26 – May 4 with YuHuai Wang (NSYSU). Work focused on an intensive survey near Dongsha Island, extending out to the 900-m isobath. Our work was loosely collaborated with a simultaneous survey of the OR1, occupying the APL/UW mooring line along 21°N (Fig. 1).

To date, our analysis of 2005 survey data has focused on quantifying the wave and turbulence conditions on the continental shelf to the shelf break, between the 40-m and 300-m isobaths. Our measurements of the in-situ density structure and turbulence energy provided the finest temporal and spatial resolution of any system used during the survey. We observed an abundance of nonlinear wave activity, but not the clear soliton-like waves of Luzon origin. We believe that the environmental stratification clearly controlled the wave behavior we observed. Unlike the conditions documented during ASIAEX in 2000 (Gawarkiewicz et al 2004, Duda et al. 2004), we found that the on-shelf

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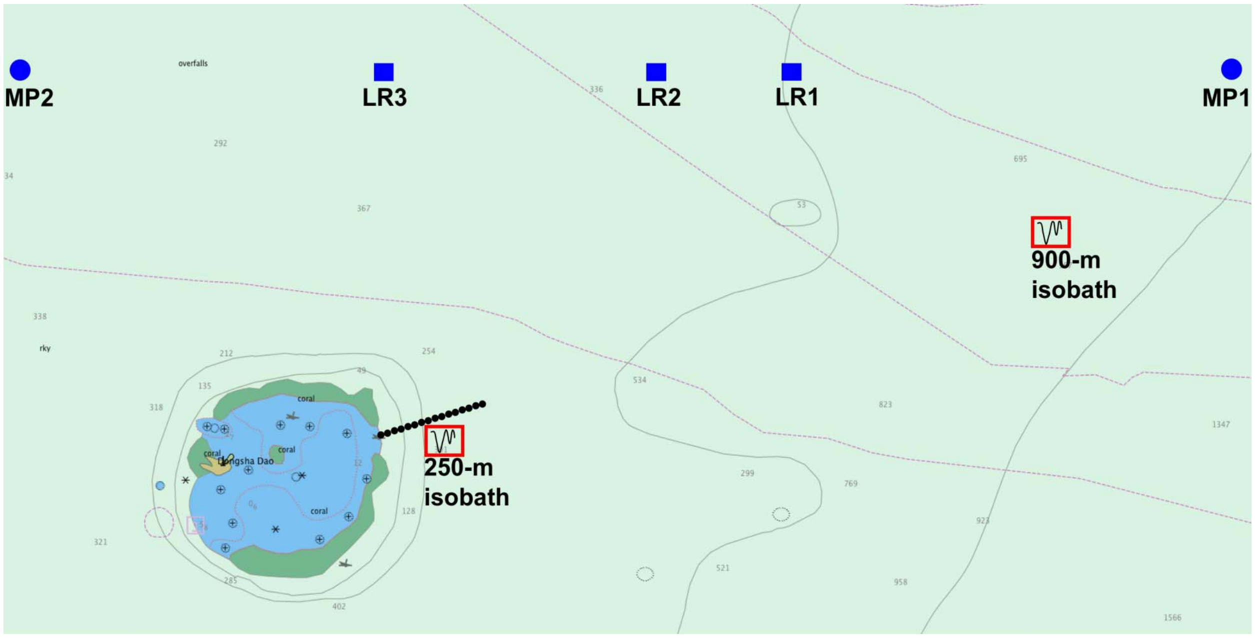

Figure 1. Map showing the survey regions for FSU turbulence measurements in the South China Sea during 2007. The OR3 surveyed sites along the Dongsha Plateau, including an intensive survey near Dongsha Island (dotted section). Sample locations showing a nonlinear wave in a red box denote locations of intensive observations of Luzon waves. The APL/UW mooring/ADCP array is denoted by locations marked with "MP" for moored profilers and "LR" for ADCP long rangers.

stratification in 2005 was considerably deeper. This allowed for the conversion of depression waves to elevation waves near the 100-m isobath. This further resulted in substantial conversion and dissipation of Luzon waves prior to their arrival on the shelf. Thus, soliton-like depression waves from the deep SCS basin were not being transmitted onto the shelf during 2005. We believe the observations in 2005 were the first to document the SCS shelf in this deep stratification state.

Despite the lack of observed soliton-like waves, we observed substantial baroclinic activity at all sites along our survey. Long trains of depression waves were observed shoaling at the shelf break. In at least one case, a large-amplitude depression had energy characteristics of a Luzon wave, suggesting this pulse was the evolved remnant of a deep basin soliton. Near bottom elevation waves were also observed at the shelf break, in one case reaching 40-m amplitude, or roughly 1/3 of the water depth. Elevation waves were observed in water as shallow as 40-m, propagating along the buoyancy-gradient maximum as it shoaled toward the Chinese coast. It appears that much of the on-shelf baroclinic activity is the result of locally generated waves.

During 2007, our work focused on observing wave activity on the Dongsha Plateau (Fig. 1). The study site was chosen based on modeling results that showed that Luzon waves focused a primary beam of baroclinic energy into this region. The Plateau region's bathymetry is in contrast to the shelf break. The region east of Dongsha Island slopes only gradually from 300-m to 500-m, but then steeply drops into the deep basin. Thus, Luzon waves abruptly shoal from the 3000-m isobath to the 500-m isobath, but then propagate along the plateau shoaling gradually to about 250-m depth.

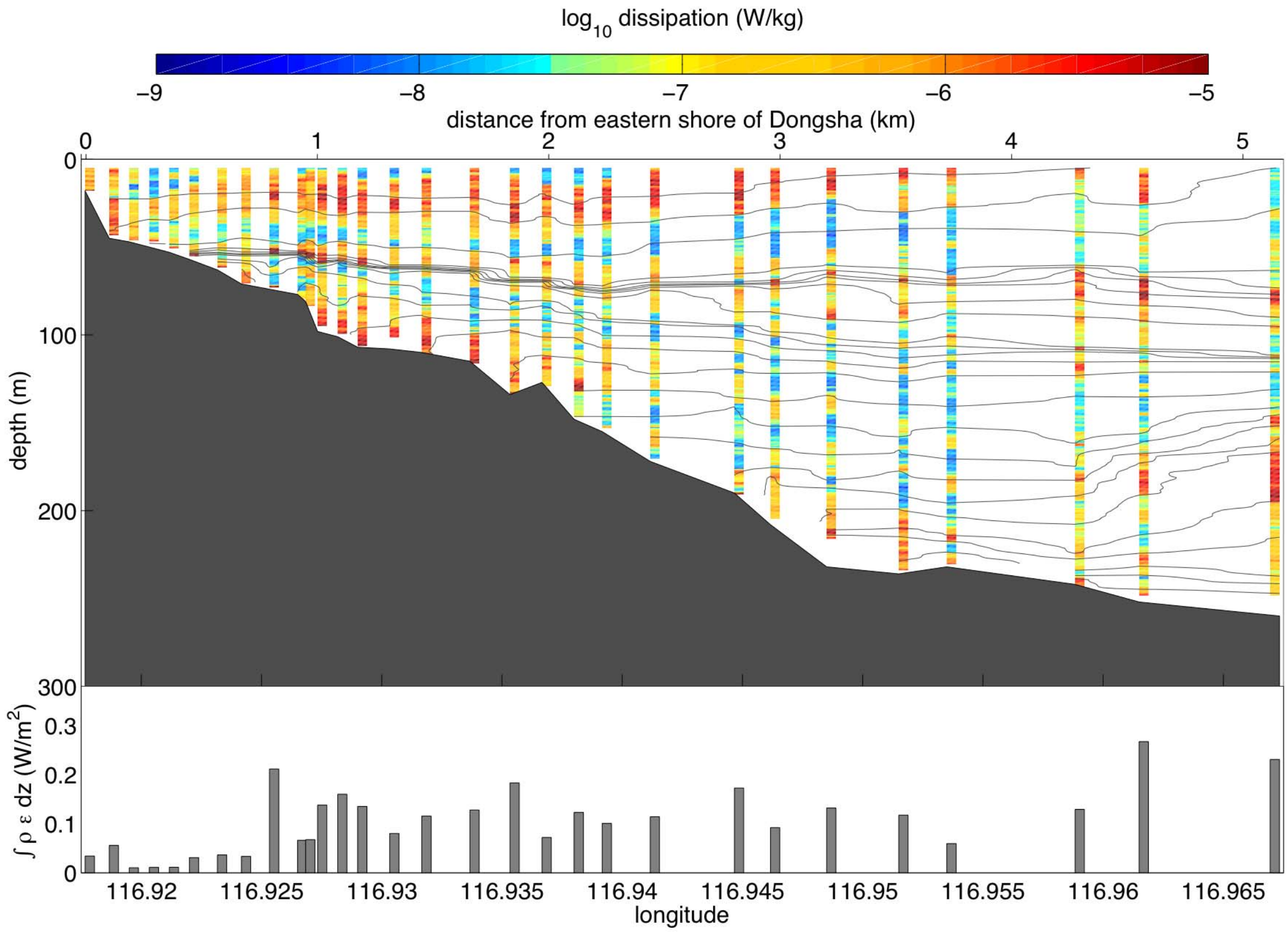

Figure 2. Section extending away from the eastern shore of Dongsha Reef, along the survey leg indicated in the map in Fig. 1. The temperature field is contoured, and turbulence dissipation rate profile data is shown in color according to the logarithmic color bar. Depth integrated dissipation levels are shown along the lower panel.

Our study focused on mixing processes close to Dongsha Island (Fig. 2). Over 100 full-depth profiles were collected over a 5 day period directly along the east and west edges of the island. Along the eastern side of the Island, we conducted a survey between the 20-m and 250-m isobaths. This survey was conducted between arrivals of a Luzon waves, and shows that considerable levels of turbulence persist even during times when the waves are not present. The integrated dissipation levels at this site are three-times larger than similarly measured dissipation levels along the continental shelf slightly north of the Dongsha Plateau. Prof. Wang's work at NSYSU has demonstrated that the breaking of Luzon waves near the island leads to mixing levels that influence biological activity along the coral reef.

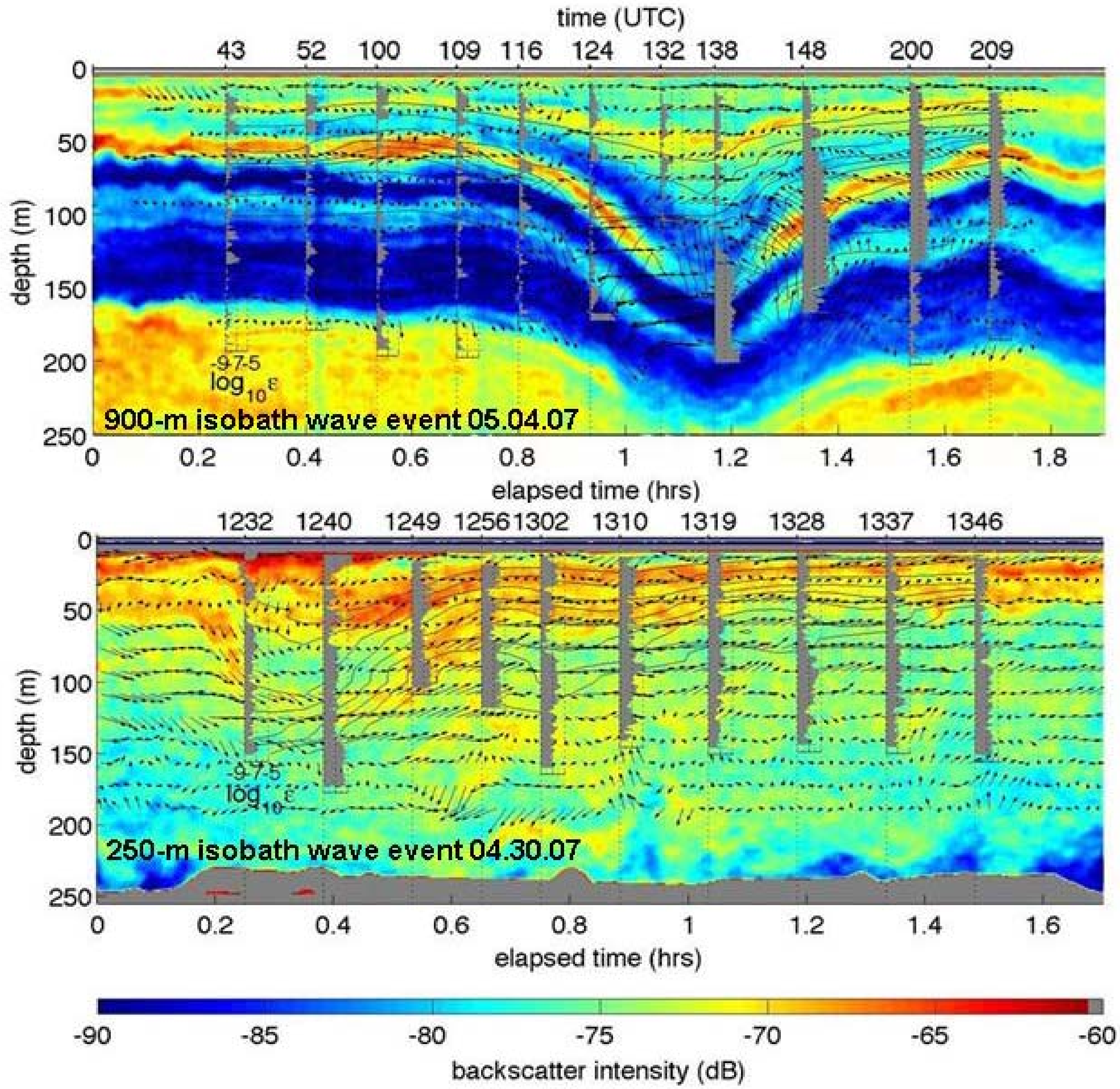

Figure 3. Measured property fields of two survey wave events on the Dongsha Plateau. The upper panel shows a wave over the 900-m isobath; the lower panel shows a wave over the 250-m isobath. Acoustic backscatter is shown according to the color bar. Temperature contours, ADCP velocity vectors, and turbulent dissipation levels are also shown.

During an additional phase of the survey, we actively surveyed two Luzon wave events. These observations were the first to document the turbulent energy within such large-amplitude nonlinear waves. Our observations will allow for a full assessment of wave energy, including dissipation terms. For now, we have focused on resolution of the acoustic backscatter, hydrographic, velocity, and turbulence fields (Fig. 2). Turbulence levels exceeding $1 \cdot 10^{-4}$ W/kg were measured in the wake of each wave; and are among the largest ever observed in the stratified interior of the ocean. We have estimated the integrated dissipation levels of 5 kW/m and 1 kW/m were found in the wave events observed at the 900-m and 250-m isobaths, respectively. This result was a surprise, as we initially expected that the waves would become increasingly more dissipative as they shoaled into shallower regions.

RESULTS

- The transmission of Luzon waves onto the shelf is sensitive to the depth of the primary stratification layer. The shelf break stratification in 2005 was deeper than in previous years, lead to a significant conversion of depression solitons into long dispersed trains of waves. These evolved Luzon waves have features similar to locally generated nonlinear waves originating from tidal forcing at the shelf break. A preliminary energy analysis suggests that wave packets of Luzon origin contain an order of magnitude more energy than the locally generate shelf waves.

- The Dongsha Plateau favors the preservation of soliton-like structure as the waves shoal up the continental slope. The initial shoaling past the 1000-m isobath clearly leads to significant dissipation throughout the wave structure, though this is not enough to destroy the solitons-like form of the waves. Shoreward of the 500-m isobath, the more gradual bottom slope of the plateau allows the remaining wave structure to propagate a considerable distance.

- No clear "graveyard" of nonlinear wave energy was found. Luzon waves shoaling past the shelf break are mixed with locally generated waves, all of which are acted on by dissipative drag with the surface and bottom boundary layers over the broad continental shelf off China. Luzon waves propagating along the Dongsha Plateau either collide with the Island, or dissipate over a considerable time and distance, loosing energy over the gradually sloping bathymetry.

- Our limited survey suggests that the most significant sink in the Luzon wave energy budget occurs during the initial shoaling over the continental slope, between the 500-m to 1500-m isobaths.

IMPACT/APPLICATIONS

The new data collected in the 2007 observational program provides the first picture of the spatial and temporal signals of nonlinear internal wave fine- and microstructure on the Dongsh Plateau of the South China Sea. These measurements, in conjunction with model simulations and the efforts of other groups, will establish the basis for an internal-wave climatology of this important WestPac region.

RELATED PROJECTS

The PI has worked closely with two other investigators modeling SCS waves. Harper Simmons (UAF) is a co-PI on the FSU South China Sea 2007 field effort. He has provided considerable modeling support for the overall SCS NLIWI program. Chris Jackson (GOA) has provided a model to wave-phase prediction, largely on remotely sensed imagery of the surface manifestation of the waves.

Both the UAF and GOA models were used extensively during the 2007 field program for prediction of wave events, and both models proved to be excellent resources. In general, both models were accurate to within 30 to 90 minutes in phase prediction. Predictions for waves tended to lead observations for sites very close to Dongsha Island, but were otherwise very close for waves propagating in water deeper than 500 m. An example of a GOA prediction is shown in Figure 4, for the wave we observed at the 900-m isobath on 4 May 2007 (Figure 3, top panel).

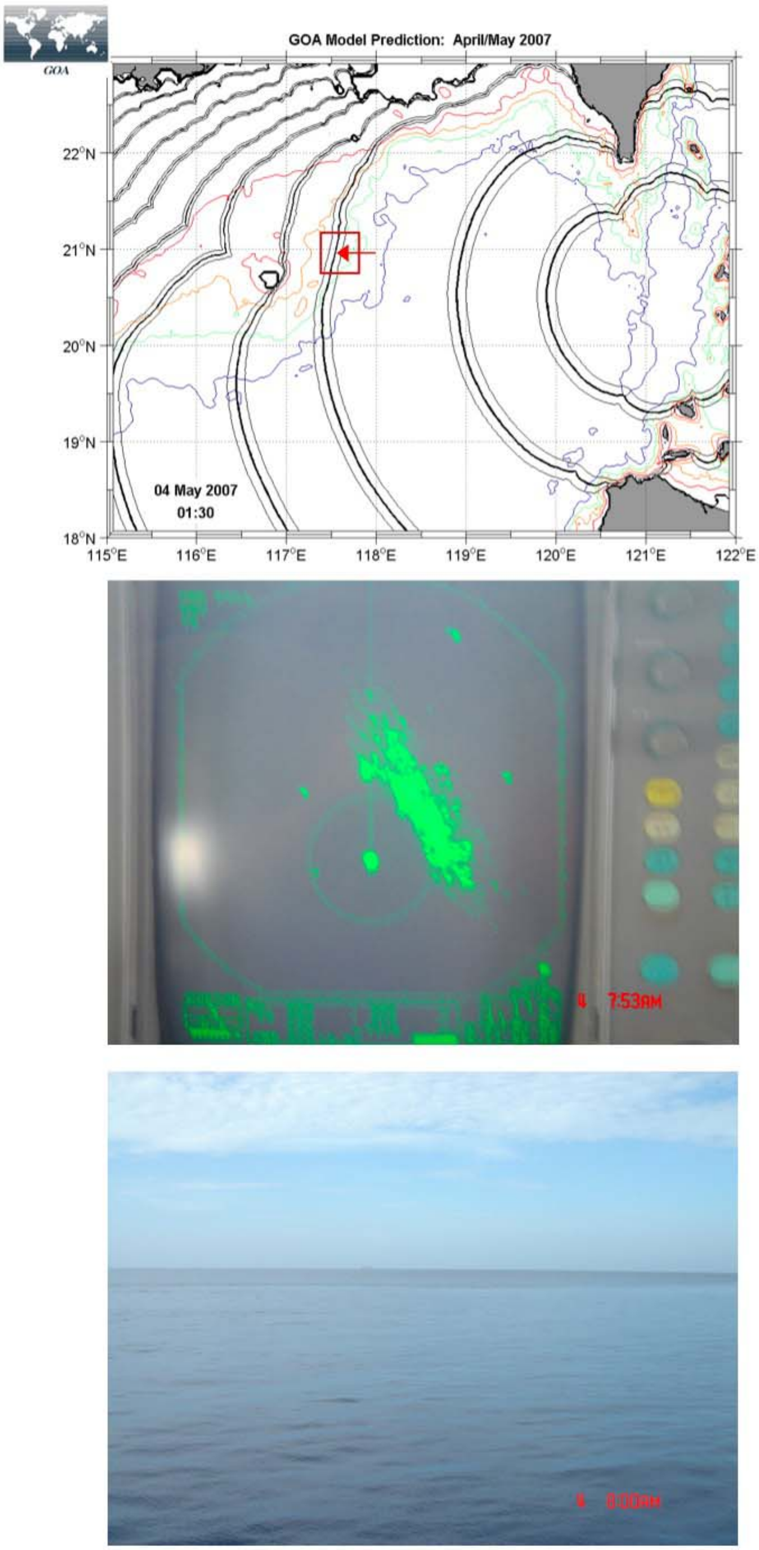

Figure 4 GOA prediction for a wave arrival at the 900-m isobath just east of Dongsha Island on 4 May 2007 at 0130 UTC, corresponding to 0930 AM local time. The wave was observed to arrive within 15 minutes of this time (see Figure 3, upper panel). The image of the shipboard radar display, and a photograph of the sea-surface, show the wave coming from about 5 km away. Times shown in the photos indicate local time.

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